Fundamental Studies In Tropical Cyclone Structure & Intensity Change

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LONG-TERM GOALS AND OBJECTIVES

Focusing on dynamical and thermodynamical processes germane to the hurricane's core region, the objectives of this research project are to obtain a more complete understanding of atmospheric processes governing hurricane development, structure and intensity. This year we have continued our basic research on the dynamics and thermodynamics of the hurricane eye/eyewall region, and the dry adiabatic dynamics of a hurricane-like vortex in vertical shear. We have also begun an applied research thrust, in collaboration with Dr.'s N. Davidson and K. Tory of Australia's BMRC. New insight and discoveries have been advanced in all areas. These are summarized below.

- **A New Look at the Problem of Tropical Cyclones in Vertical Shear Flow: Vortex Resiliency**

APPROACH

A simple model based on the Boussinesq Primitive Equations (PE), linearized about a mean barotropic vortex in gradient and hydrostatic balance is used as a baseline model for exploring the tilting behavior of tropical-cyclone-like vortices in unidirectional vertical shear flow. In our previous work (Reasor and Montgomery 2001; Schecter, Montgomery, and Reasor 2002) a self-alignment mechanism was identified which reduces departures from an upright state (i.e., the vortex tilt). The mechanism involves the projection of the vortex tilt onto vortex Rossby waves (VRWs) and their subsequent damping. The question we sought to address in this work was how this VRW damping mechanism operates when the vortex is embedded in a vertical shear flow. The linear PE model is used for acquiring a first order understanding of the basic dynamics of the vortex-shear interaction. It is well known, however, that for a given vortex strength, as the shear strength increases, the vortex crosses a threshold and irreversibly shears apart. To explore the nonlinear aspects of this problem the dry dynamical core of the fully nonlinear, nonhydrostatic, incompressible version of the CSU-RAMS (Pielke et al. 1992) model was used. This research was conducted by P. Reasor, M. Montgomery and L. Grasso at CSU.

WORK COMPLETED AND RESULTS

As detailed in Reasor, Montgomery, and Grasso (2003; in press, hereafter RMG03), the main breakthrough was the development of a new paradigm for the tropical cyclone in vertical shear problem. Using the linear PE model and nonlinear CSU-RAMS model, we demonstrated that hurricane strength (initially barotropic) vortices can remain nearly vertically upright in vertical shears

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in excess of 10 m/s over the depth of the vortex without the direct aid of cumulus convection. The resiliency is ascribed to the intrinsic VRW damping of the vortex tilt. To first order, a tilted vortex in vertical shear behaves as a forced, damped harmonic oscillator in the perturbation potential vorticity amplitude. When the intrinsic damping rate and precession frequency of the vortex is large compared to the differential advection rate associated with the vertical shear flow, the vortex remains nearly upright. On the basis of this finding, we argued that the axisymmetric component of the diabatically-driven circulation in hurricanes contributes indirectly to vortex resiliency against shear by increasing the Rossby number (without convection, of course, the mean vortex would spin down under frictional drag in the boundary layer) and enhancing the radial gradient of azimuthal-mean potential vorticity. The results suggest that deep cumulus convection in the eyewall of the storm, in addition to reducing the local static stability in moist ascent regions, increases the efficacy of the VRW damping mechanism. A second significant result is the prediction of a downshear-left steady state tilt for vortices whose damping rate is non-negligible and precession frequency is much greater than the vertical shear differential advection rate. This behavior (see Fig. 1) is predicted by our linear harmonic oscillator model and it has been verified using the CSU-RAMS model for a vortex resembling Hurricane Olivia's (1996) horizontal (but barotropic) structure.

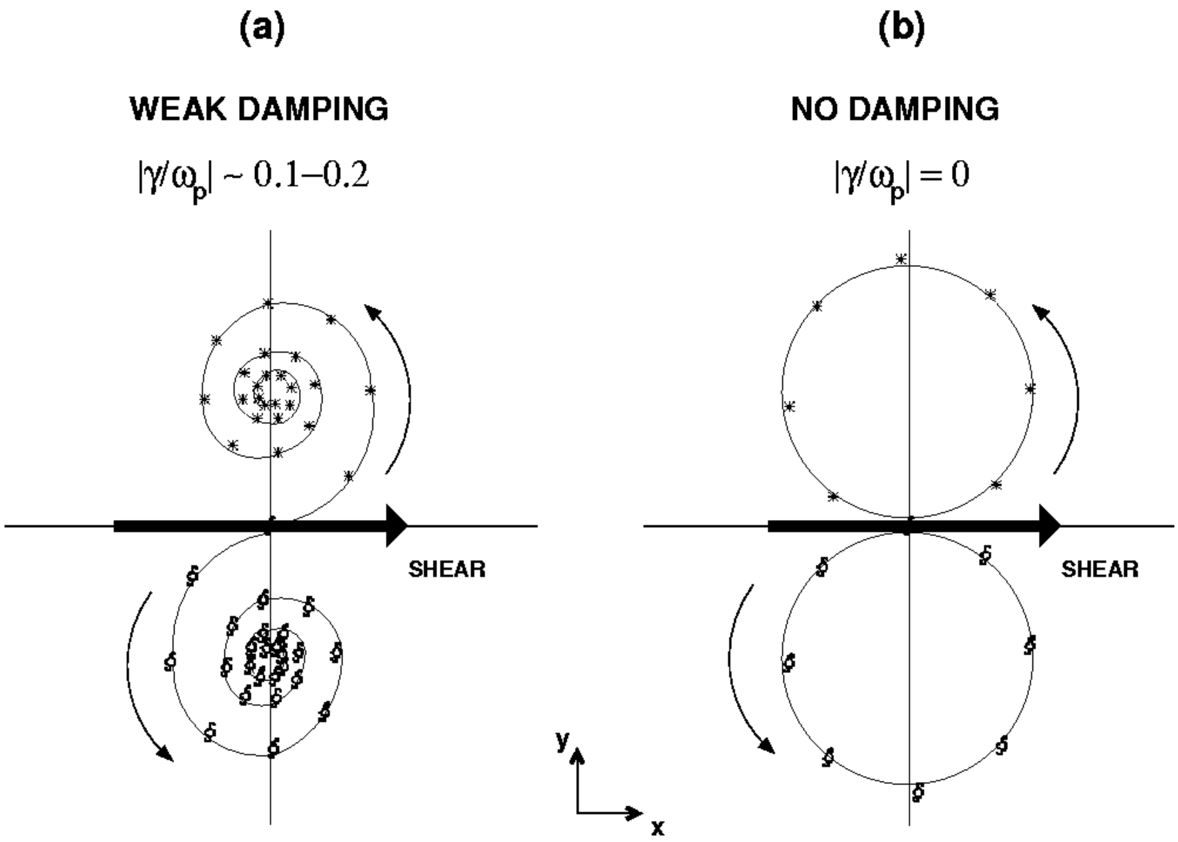


Figure 1: Schematic illustration of the vortex tilt for the case where (a) the VRW damping rate γ is a non-negligible fraction of the precession frequency ω_p and (b) the VRW damping rate is zero. The initially aligned vortex is tilted by westerly vertical shear. The vortex center at upper levels is denoted by the stars, and at lower levels by the hurricane symbols. The thin arrows indicate the direction of motion of the upper- and lower-level centers. The vortex in (a) achieves a steady-state tilt to the left of the vertical shear vector. In (b) the vortex tilts downshear, precesses cyclonically upshear, realigns, and then repeats this evolution.

IMPACT/APPLICATIONS

The impact of this work is twofold. First, it suggests a useful conceptual simplification of the hurricane-in-shear problem. One need no longer invoke deep cumulus convection as the primary mechanism for the resiliency of hurricanes in vertical shear flow. Of course, diabatic processes are needed to maintain the azimuthal mean vortex against frictional drag in the boundary layer. This balance is already implicit in the linear model -- the mean vortex is unchanged, assumed to be maintained by the diabatically-driven axisymmetric circulation (the effect of vertical shear on the convective distribution is neglected in this idealized framework). Vortex resiliency is due to the VRW damping mechanism, which DIRECTLY reduces the vortex tilt. Second, the analytical prediction of a downshear-left orientation for the hurricane-like vortex in shear helps explain why convection appears downshear-left in observed hurricanes, and does not precess around the vortex as some previous dry idealized studies using unrealistic basic state radial profiles for the relative vorticity would suggest. This theoretically predicted steady state solution is currently being tested in a full physics cloud resolving numerical modeling context with encouraging results.

FUTURE WORK

In the upcoming year we will examine how explicit moist processes influence the hurricane-in-shear problem.

- **Evaluating the Significance of the Hurricane Turbocharger**

APPROACH

Persing and Montgomery (2003; PM03a) introduced the hurricane "turbocharger" to explain the occurrence of extremely intense axisymmetric hurricanes produced by an axisymmetric hurricane numerical model at high spatial and temporal resolution (e.g.Rotunno and Emanuel 1987; RE87). A beneficial entrainment of eye air by the ascending air in the eyewall was shown to allow for extra heat to be produced by condensation. The extra heat added to the hurricane eyewall was interpreted as a Carnot turbocharger, extending the Carnot engine analogy of Emanuel (1986; 1995). Because of this added heat, the simulated hurricanes greatly exceeded Emanuel's maximum possible intensity theory (Emanuel 1995). The tendency for high-resolution numerical models to exceed Emanuel's upper bound for hurricane intensity is termed "superintensity". Our current research has focused on determining the robustness of this result in varied circumstances by gradually adding layers of complexity upon the "idealized'' benchmark provided by the RE87 model. In this spirit, a sequence of simulations has been conducted using the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992; Cotton et al. 2003) and MM5. Research to date using RAMS and MM5 has been conducted by J. Persing, M. Montgomery, M. Nicholls, and T. Cram at CSU.

WORK COMPLETED

We have completed a suite of RAMS simulations that demonstrate the existence of the turbocharger mechanism in three-dimensional geometry.

RESULTS

A version of RAMS has been developed to replicate the highly simplified physics of the RE87 model as closely as possible. The necessary physical simplifications were: 1) Newtonian cooling as a substitute for longwave radiative energy losses, 2) a bulk aerodynamic surface formulation for surface drag and exchanges of heat and moisture, 3) no shortwave radiation (energy input solely through a fixed ocean temperature), 4) no ice, and 5) f-plane with a convectively neutral initial sounding (RE87). The two areas where this simplified version of RAMS differs from RE87 is three-dimensional geometry and the RAMS rain package. For each of the five simplifications listed, a simulation was performed of increasing complexity (each closer to the standard configuration of RAMS). The results demonstrate that superintensity persists through these increasing degrees of complexity, and the turbocharger as described for an axisymmetric model (PM03a) appears to be strongly active in these three dimensional hurricane simulations as well.

IMPACT/APPLICATIONS

The RAMS simulations confirm that the beneficial entrainment of low-level eye air into the eyewall can also be active in three dimensions. This is not a trivial result because the nature of the mixing process is generally quite different in three dimensions. Since superintensity is completely absent in extant theories for hurricane intensity, we believe that presently available maximum potential intensity (MPI) theories must be applied with caution. We believe this work points to new basic and applied research opportunities that will lead to the improvement of hurricane intensity forecasting

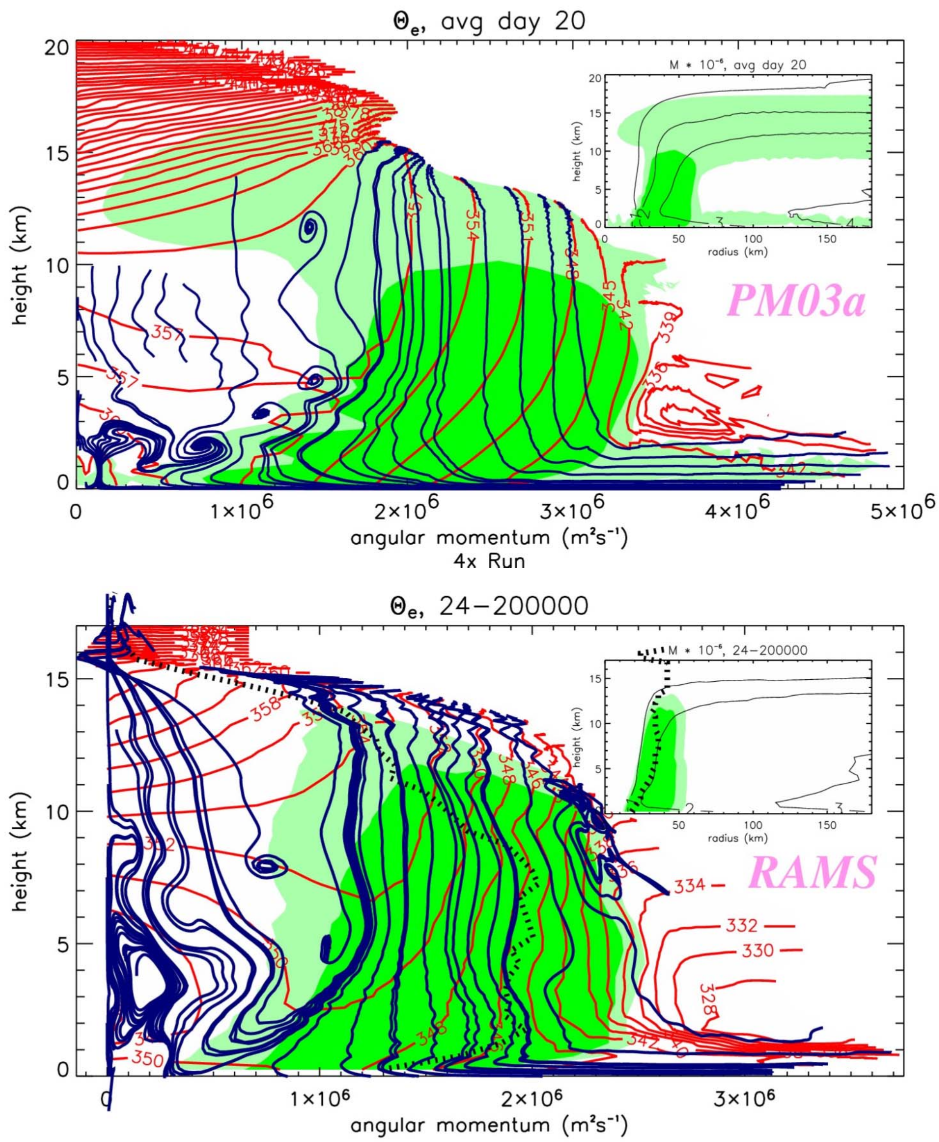


Figure 2: Eyewall schematic in hurricane simulations from PM03a (top) and from our simplest RAMS simulation (bottom). When Emanuel's MPI theory is obeyed, blue streamlines are parallel to red contours of Θ_e within the eyewall (green shading) and are perfectly vertical. The inset provides physical reference for the angular momentum coordinate, comparing the structure of hurricane simulations from PM03a (top) and from our simplest RAMS simulation (bottom).

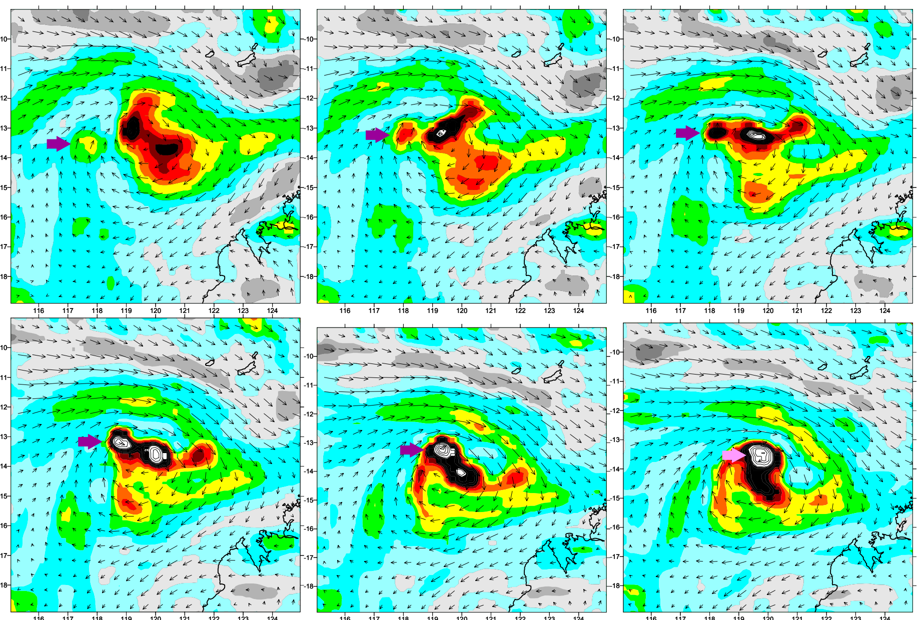
FUTURE WORK

In the upcoming year, we will examine the mixing processes that occur between the eye and eyewall in the three-dimensional RAMS simulations. We anticipate that the mixing occurs by a combination of continuous transfer of matter from the eye and more-or-less regular recurrences of episodic bursts of mixing. Eyewall mesovortices (Montgomery et al. 2002) are an obvious candidate for strong lateral mixing between the eye and eyewall regions, but this hypothesis requires a thorough evaluation in the current modeling context.

- **Analysis of Genesis and Intensification in the Australian Operational TCLAPS Model**

APPROACH

The Australian Bureau of Meteorology's operational tropical cyclone (TC) forecast model (TCLAPS) has been used to successfully predict TC genesis and development (without a bogus). Convective bursts lasting 6—12 hours feature in many simulations, and appear to play a pivotal role in enhancing vorticity in the vicinity of the convection. This process is believed to be responsible for TC genesis and development in a number of simulations in which the environment is favorable for development (i.e., weak vertical wind shear and large-scale cyclonic vorticity). This process is an example of "bottom-up" development; a theory for describing TC genesis and intensification that is gaining observational credence in the peer-reviewed literature (e.g. Molinari et al. 2003). This research has been conducted by K. Tory of BMRC and M. Montgomery of CSU.



COLOR SCALE KEY

Grey: PV > 0 (anticyclonic)
Ice Blue: 0 to –0.2 PV units
Blue: -0.2 to –0.4 PV
Green: -0.4 to –0.6 PV
Yellow: -0.6 to –0.8 PV
Orange: -0.8 to –1.0 PV
Red: -1.0 to –1.2 PV
Dk Red: -1.2 to –1.4 PV
Black: -1.4 to –2.4 PV
White inside black: <-2.4 PV

Purple arrow: position of convective burst

Figure 3: Ertel Potential vorticity (PV, shaded) and horizontal winds (vectors) on the σ=0.85 surface, from a numerical simulation of TC Chris off the west coast of Australia (1200--2200 UTC, February 1, 2002) using the TCLAPS.

WORK COMPLETED AND RESULTS

Figure 3 illustrates the Ertel potential vorticity (PV) structure on the σ=0.85 surface at two hourly intervals during the genesis stage of a simulation of TC Chris (2002). It shows localized development of PV associated with a sustained burst of convection initially to the west of the main larger-scale and more-intense region of cyclonic PV. With time, this PV feature intensified until it became dominant and served to focus the surrounding PV anomalies and environmental PV through a process of vortex merger and axisymmetrization (Enagonio & Montgomery 2001, and refs.). The net effect was to greatly enhance the large-scale vorticity, which continued to intensify into tropical storm strength within the next 24 hours. Gray (1998) identified similar behavior in convective bursts he termed 'extreme convection' (EC).

IMPACT, APPLICATIONS AND FUTURE WORK

Detailed investigations into the nature and structure of the simulated convective bursts are underway. The development of diagnostic software, designed to unravel the temporal development of model processes that trigger the convective bursts, is nearing completion. We plan to investigate environmental conditions that do and do not favor development by this process. Preliminary studies with the TCLAPS have identified surprising vortex resilience in the presence of intense environmental shear during a sustained convective burst consistent with theoretical work on sheared storms summarized above.

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HONORS/AWARDS/PRIZES

2003 Michael T. Montgomery, Colorado State University
American Meteorological Society Clarence Leroy Meisinger Award for "fundamental work in asymmetric hurricane dynamics and vortex Rossby waves"